

Ultra-Lightweight, Ductile Carbon-Fiber Reinforced Composites

Vlastimil Kunc, Pum Kim

Oak Ridge National Lab

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Project ID#: mat146

ORNL is managed by UT-Battelle, LLC
for the US Department of Energy

Overview

Timeline

- Project start date: Oct 2018
- Project end date: Dec 2023
- Percent complete: 50%

Budget

- DOE project funding: \$500K
 - DOE: 50%
 - Subcontractor: 50%
- Funding for FY22: \$200K

Barriers and Targets

- **Barrier:** Use of lower-density materials with suitable mechanical properties, i.e., materials with higher strength-to-weight and/or higher stiffness-to-weight ratios.¹⁾
- **Target:** Hybrid hierarchical CF reinforced materials that are ultralight, strong and tough for 3D printing.

Partners

- Oak Ridge National Laboratory (ORNL) -- Prime contract
ORNL project lead: Vlastimil Kunc
- University of California, Los Angeles (UCLA) -- Subcontract
UCLA project lead: Xiaoyu (Rayne) Zheng

¹⁾ source: 1. U.S. DRIVE MTT Roadmap Report, section 4

Relevance

Overall Objectives

Create hybrid hierarchical materials that are **ultralight**, **strong** and **tough** for 3D printing.

Current Limitations

- Lightweight materials: Unsatisfactory strength, toughness and weight density
- Mutually exclusive properties:
strength \longleftrightarrow toughness
stiffness \longleftrightarrow damping
- High resolution leads to a small area print, large area print lead to low resolution.

VTO's Mission

Reduce the transportation energy cost while meeting or exceeding vehicle performance expectations.


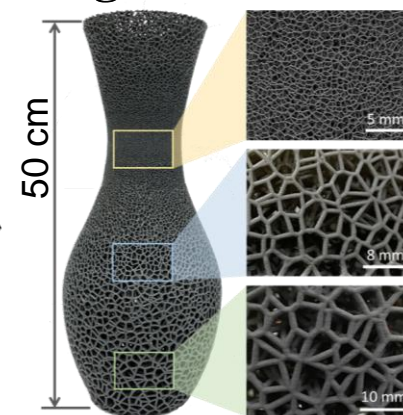
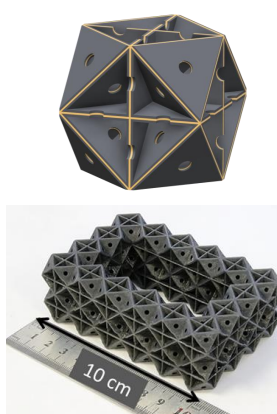
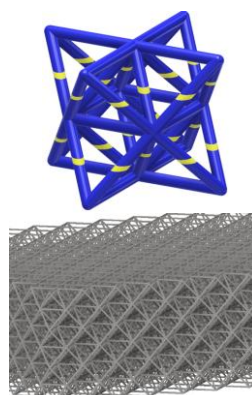
Our Strategies

- Material Combinations
 - Brittle carbon fiber and multi-material polymers
- Smart Structure
 - Optimal structure for high stiffness and high damping
- Moving stage with optics for photocuring

Milestones

Milestone	Due Date	Type	Milestone	Status
Yr 2020	4/30/2020	Regular	Demonstrated ultra-light 200 kg/m ³ hierarchical carbon fiber composites with tailored energy absorption and high strain recovery	Completed
Yr 2021	3/30/2021	Regular	3D printing of high strength CFRP close cell foams and mechanical property measurement.	Completed
Yr 2022 M.1	3/30/2022	Regular	Demonstrate hierarchical CFRP lattice materials (50 micrometer feature sizes for a high-resolution area with the overall size over ~50 cm printing areas)	Completed
Yr 2022 M.2	6/30/2022	Regular	Assemble custom extrusion system and fiber alignment mechanisms	On Track
Yr 2022 M.3	9/30/2022	Regular	3D Print multi-material CFRP samples with high damping and stiffness	On Track
Yr 2023	12/30/2023	Regular	Demonstrate multi-functional self-sensing carbon fiber reinforced composites.	On Track

System:
Multi-material projection SLA



Linear stages for extruder

Linear stages for printing platform

Light engines

Linear stage for optics

Figure 1 is a scatter plot showing the relationship between normalized absorbed energy (U/E_s) and normalized peak strength ($\sigma_{peak}/\sigma_{ys}$) for various foams. The y-axis is labeled 'Normalized absorbed energy, U/E_s (-)' and ranges from 0 to 5, with a multiplier of $\times 10^{-6}$ at the top. The x-axis is labeled 'Normalized peak strength, $\sigma_{peak}/\sigma_{ys}$ (-)' and ranges from 0 to 0.06. The legend identifies the following materials:

- Carbon foam² (purple triangle)
- Carbon microlattice² (blue triangle)
- Bi-material octet-truss³ (red circle)
- CF octet-truss³ (red triangle)
- Bi-material plate-lattices (black circle)
- CF plate-lattices (black triangle)

The data points are plotted as follows:

- Carbon foam²: $\bar{\rho} = 0.004$ (purple triangle at approximately (0.001, 0.1))
- Carbon microlattice²: $\bar{\rho} = 0.13$ (blue triangle at approximately (0.018, 2.5))
- Bi-material octet-truss³: $\bar{\rho} = 0.12$ (red circle at approximately (0.028, 1.3))
- CF octet-truss³: (red triangle at approximately (0.038, 0.8))
- Bi-material plate-lattices: (black circle at approximately (0.032, 2.6))
- CF plate-lattices: (black triangle at approximately (0.042, 0.8))

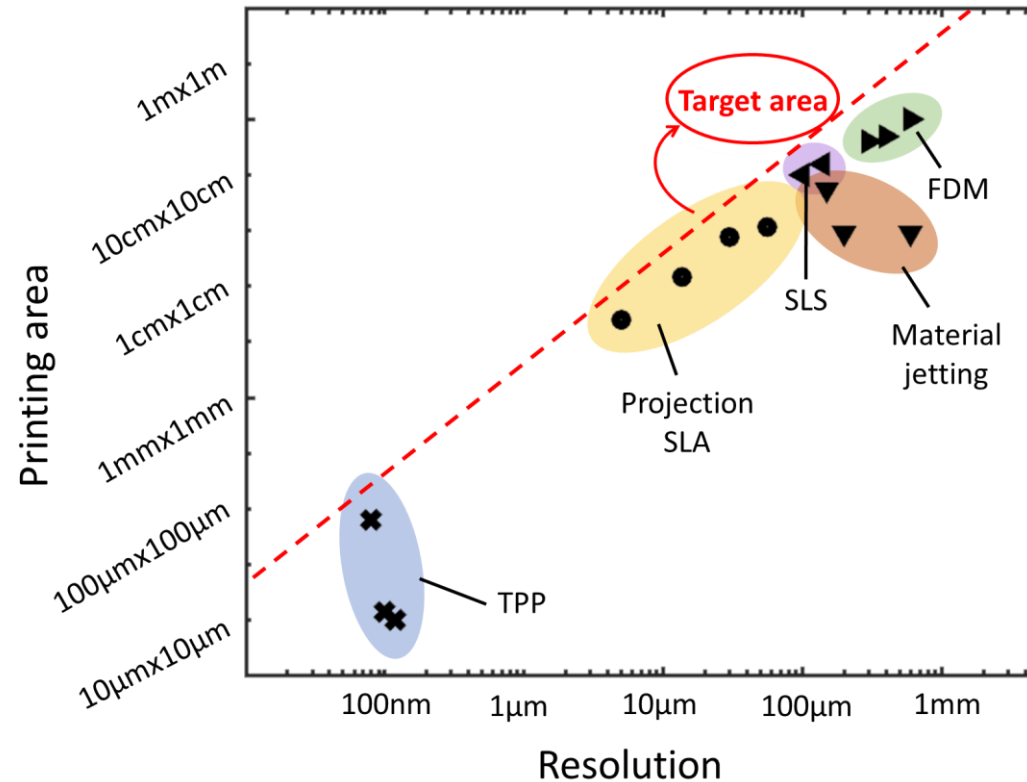
An orange oval highlights the region containing the Bi-material plate-lattices, CF octet-truss³, and CF plate-lattices, with a dashed arrow pointing from the Bi-material plate-lattices towards the CF plate-lattices, labeled $\bar{\rho} = 0.1$. The text 'This work' is placed near the CF plate-lattices. An inset plot in the top right corner shows a zoomed-in view of the data points for $\bar{\rho} \in [0, 0.2]$ and $U/E_s \in [0, 12] \times 10^{-6}$, with a solid arrow pointing from the origin towards the top right, labeled $\bar{\rho} \uparrow$.

Technical Accomplishments

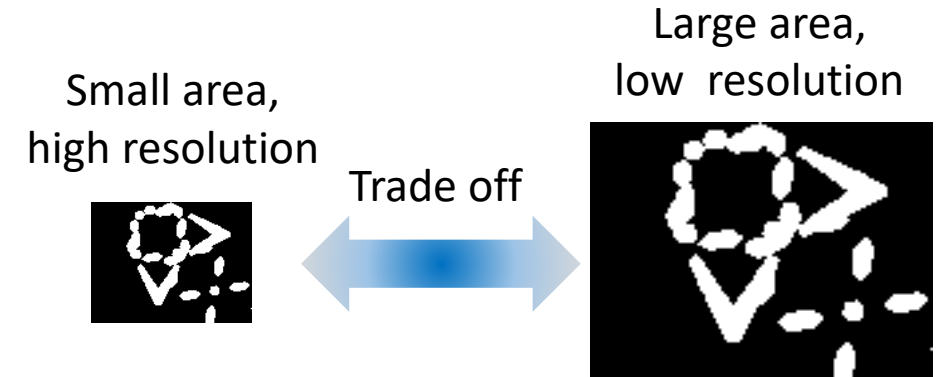
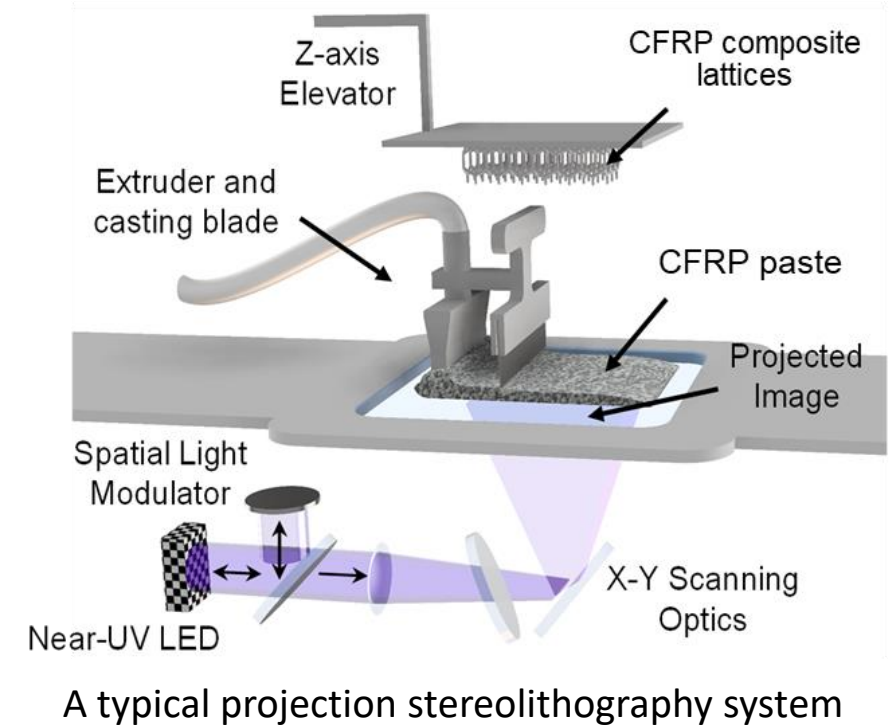
**Part 1 – Large-area projection stereolithography
system setup and demonstration of large-area
printing**

Projection Stereolithography

- Trade off between resolution and printing area.
- Most high-resolution 3D printing systems for carbon fiber composites are limited in the achievable feature size spans, with overall size span to feature resolution typically < 1000 .



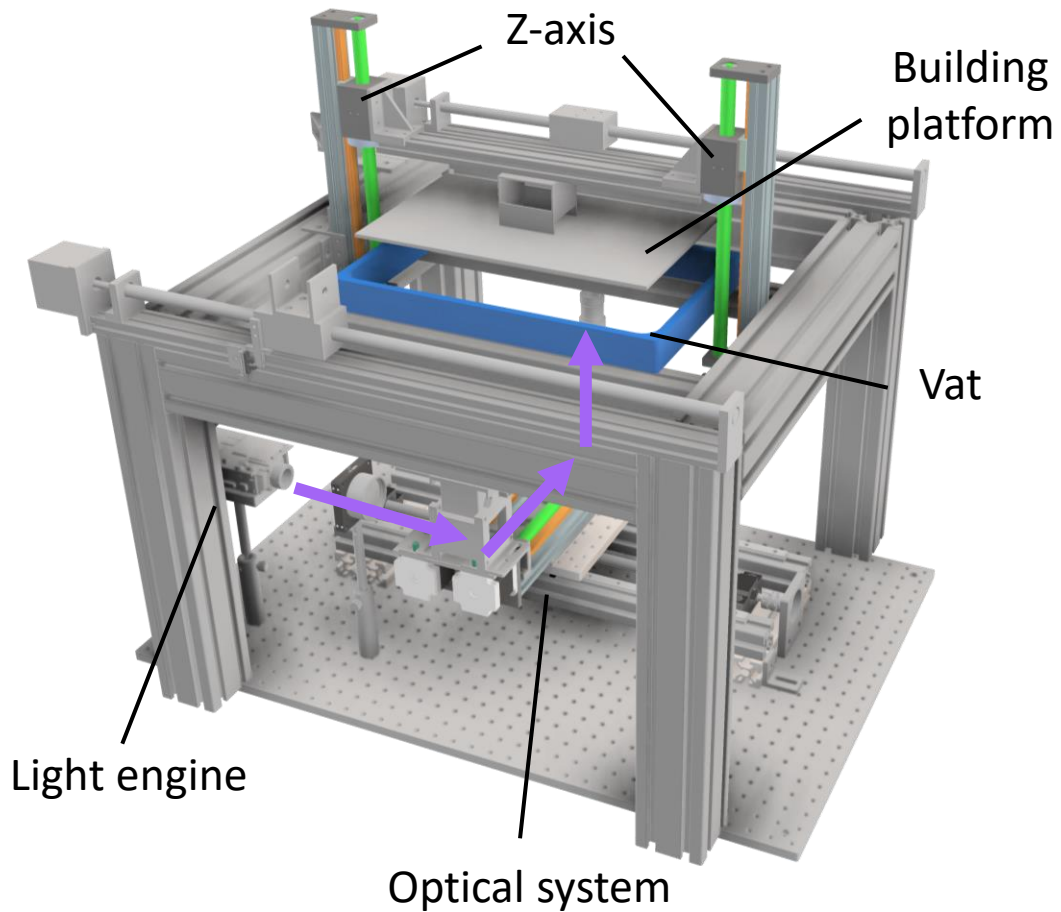
Ref: Emami, et. al., *Sensors and Actuators A: Physical*, 2014
Ge et. al., *International Journal of Extreme Manufacturing*, 2020



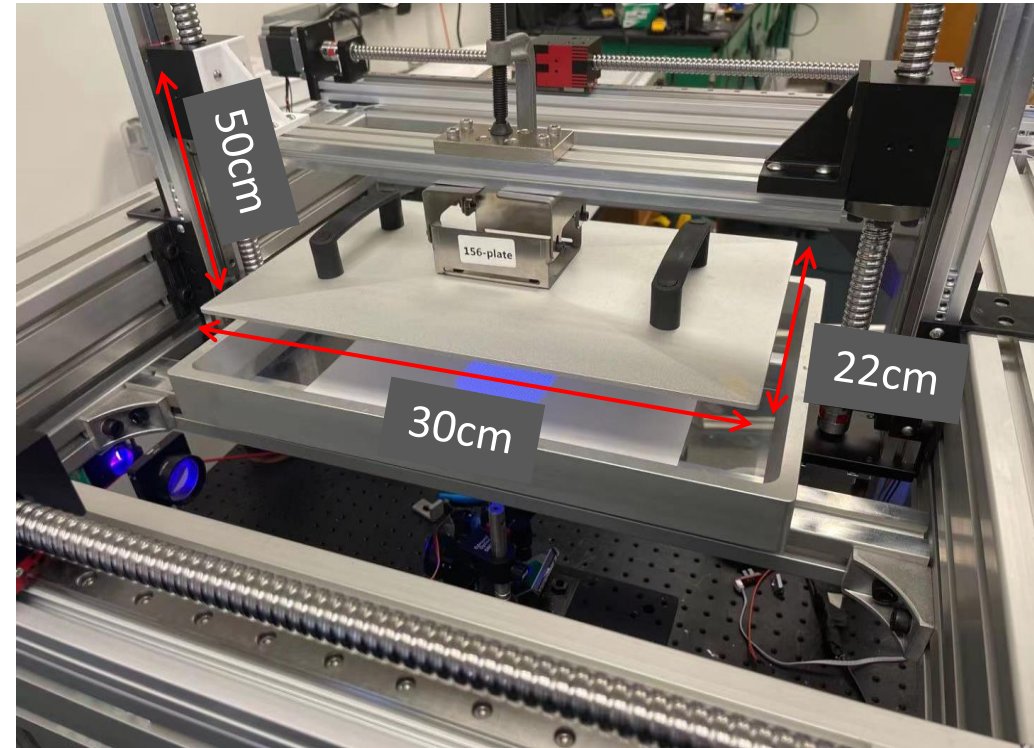
The objective of this work is to enable high-speed, large-area and high-resolution printing of carbon fiber reinforced composites.

Large-Area High-Resolution Scanning Projection Stereolithography System

Schematic of the overall setup



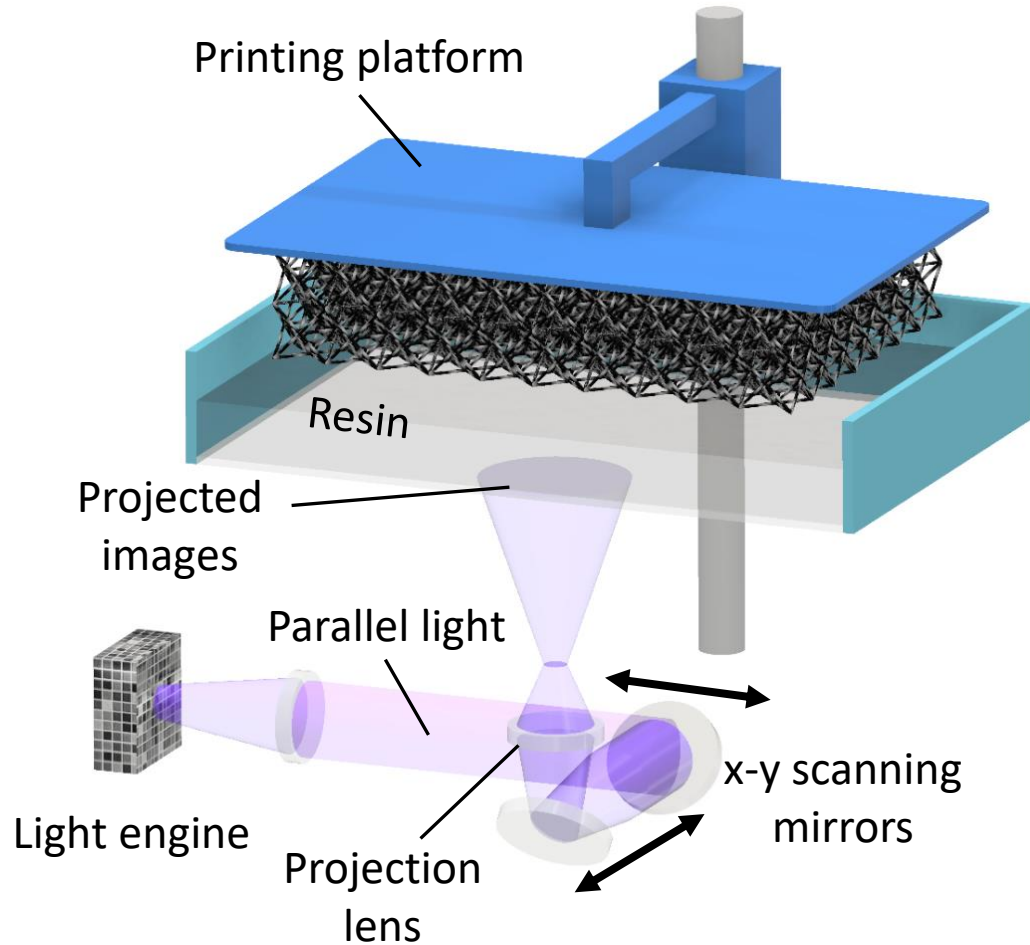
- Overall build volume: 30x22x50 cm³
- Minimal printable feature size: 50-100μm (adjustable)
- Adjustable print size/resolution



The developed large-area projection stereolithography system is comprised of a scanning projection system and a translation system, which could extend the printing area over a wide range.

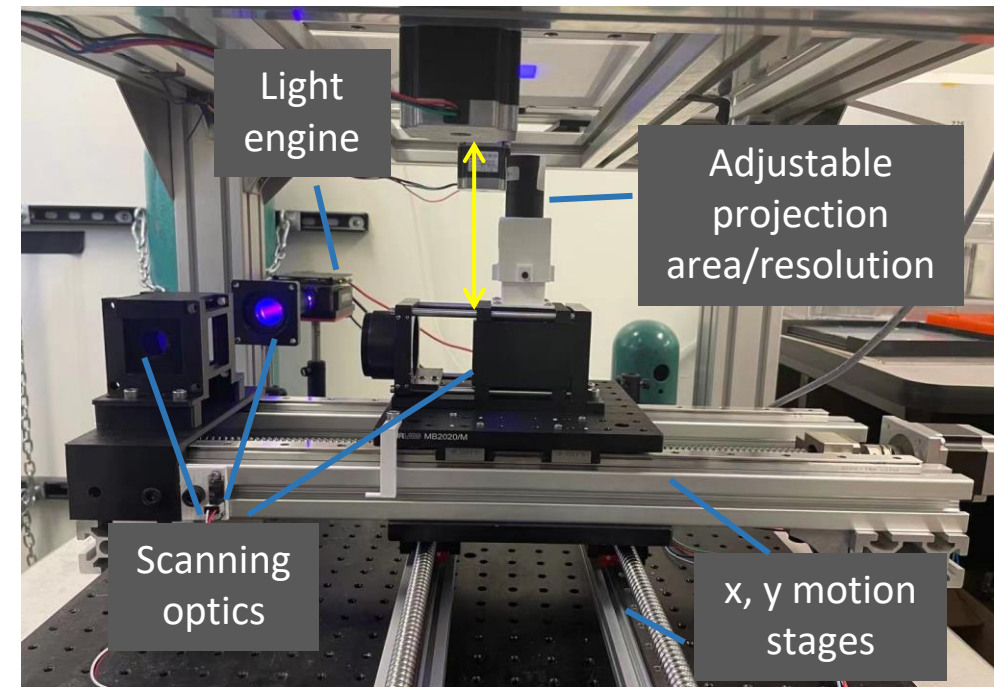
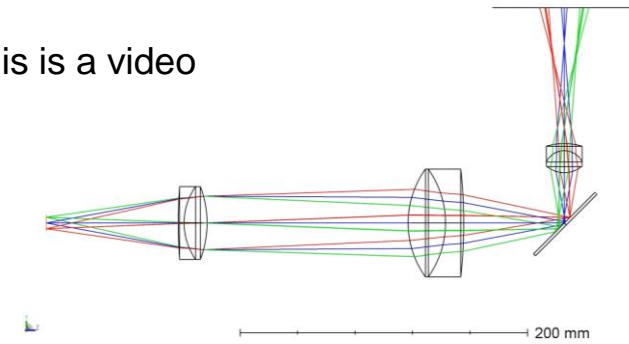
Large-Area High-Resolution Scanning Projection System

Schematic of the large-area high-resolution scanning projection system



Infinity-corrected projection design

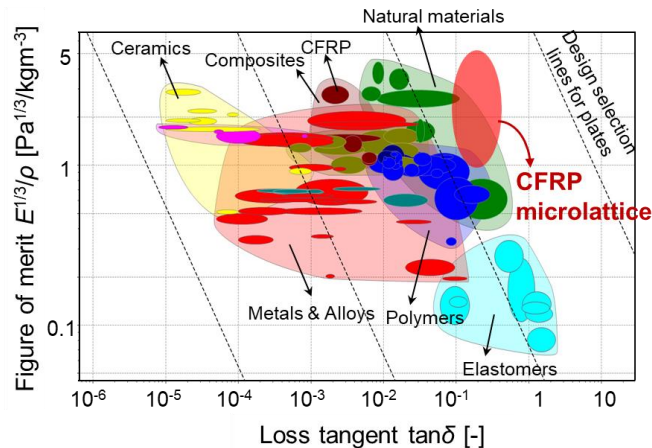
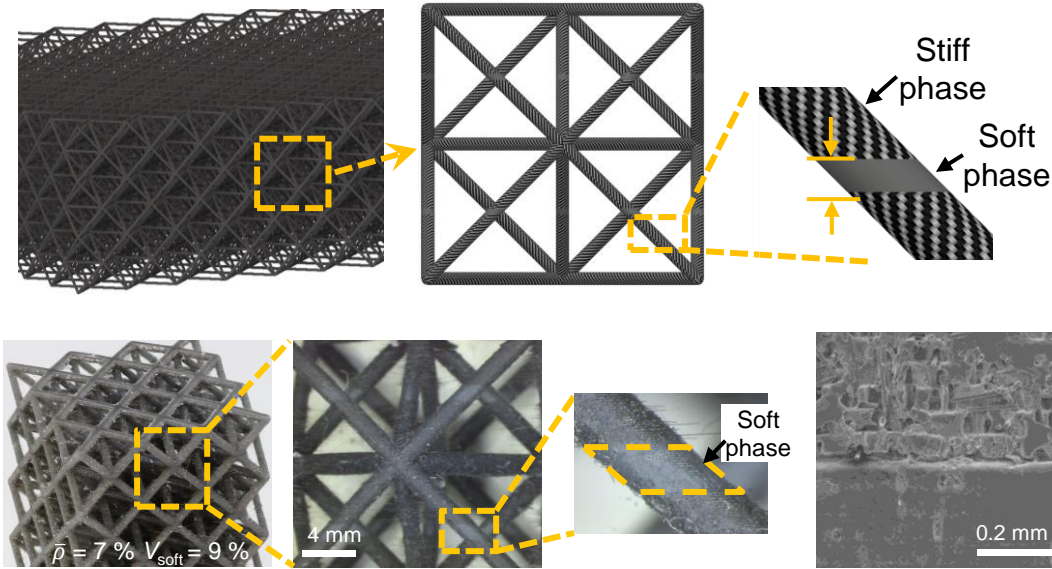
This is a video



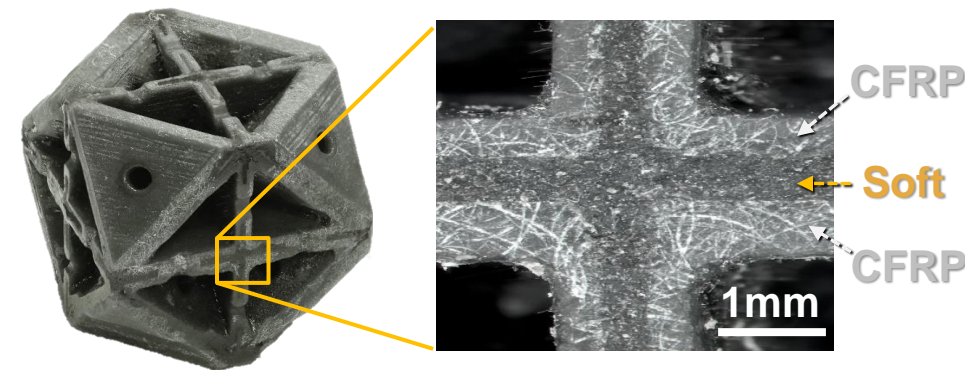
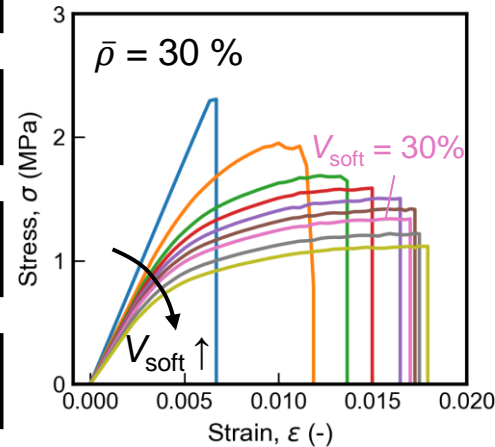
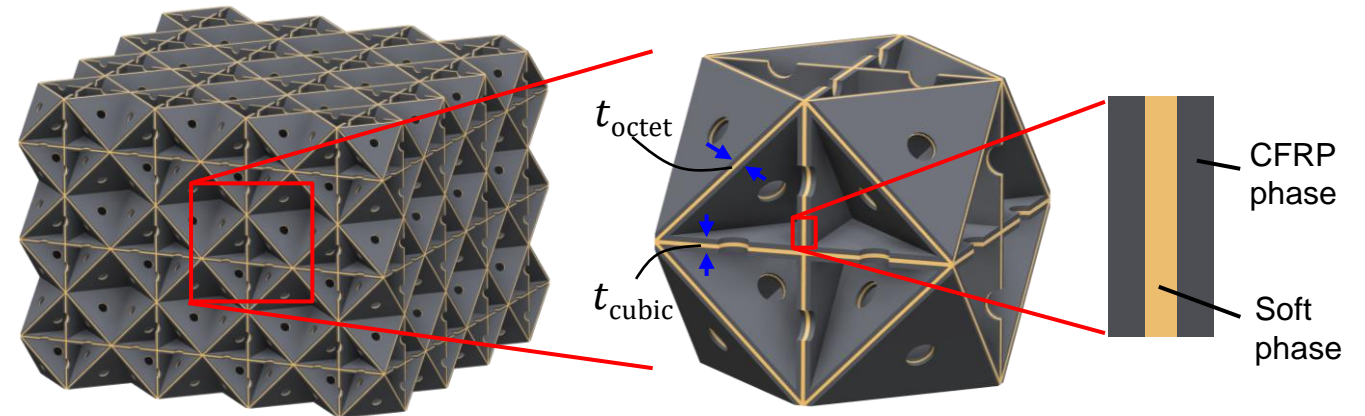
The large-area projection stereolithography system is comprised of a scanning projection system and a translation system, which could extend the printing area over a wide range.

Hierarchical Lattice

Bi-Material Octet-Truss Lattice (Yr 2020)



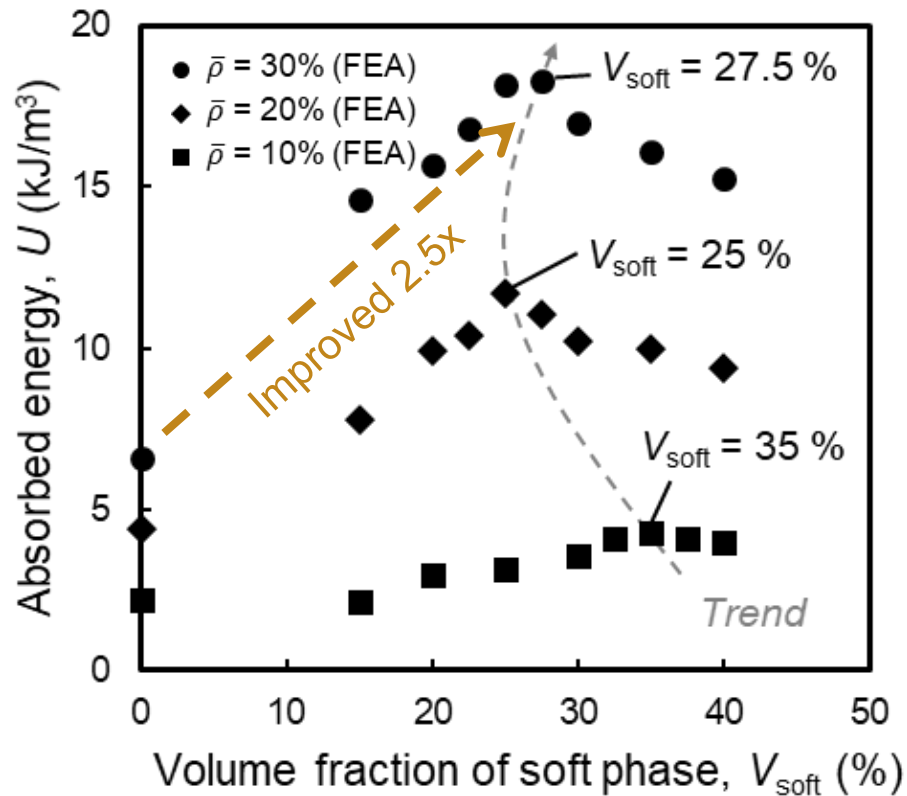
Bi-Material Cubic+Octet Plate-Lattice (Yr 2021)



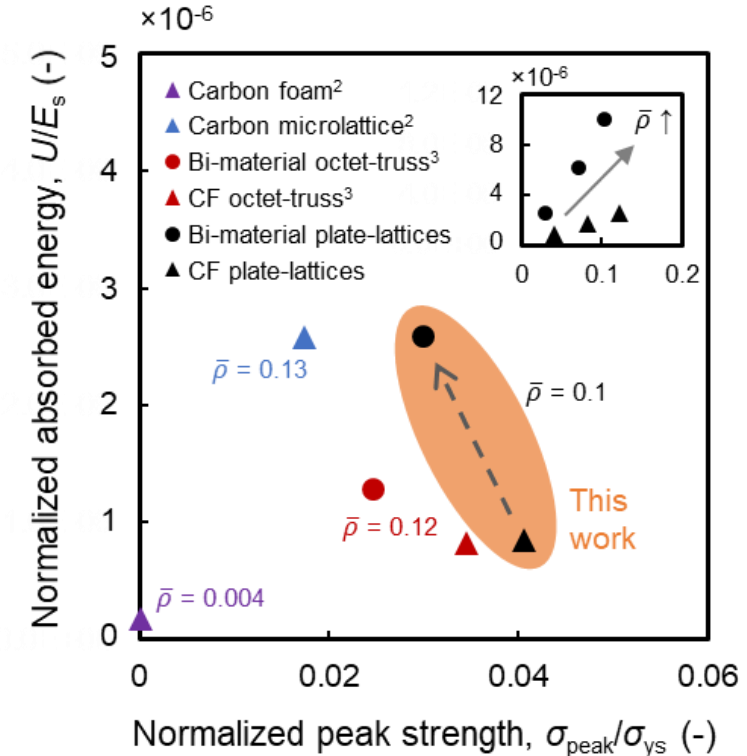
Inspired by the idea of the two-phase composite in the previous year, a bi-material isotropic cubic+octet plate-lattice was designed comprising the sandwich plate (CFRP-soft-CFRP) that can achieve high energy absorption.

High Energy Absorption Capability of the Bi-Material Plate-Lattice

(Yr 2021)



Energy absorption capability of the bi-material plate lattice is improved by introducing soft phase



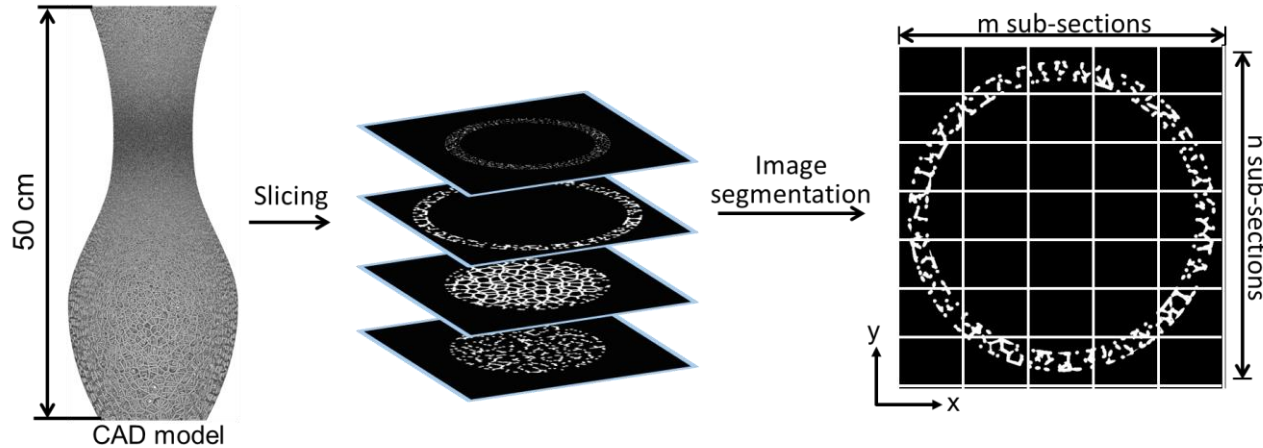
Our lattice outperforms the other reported carbon-based energy-absorbing materials in terms of the strength-energy absorption pair

Ref: [1] Jacobsen et al., Carbon, 2011
[2] Chen et al., Energy Environ. Sci., 2013
[3] Xu et al., Additive manufacturing, 2020

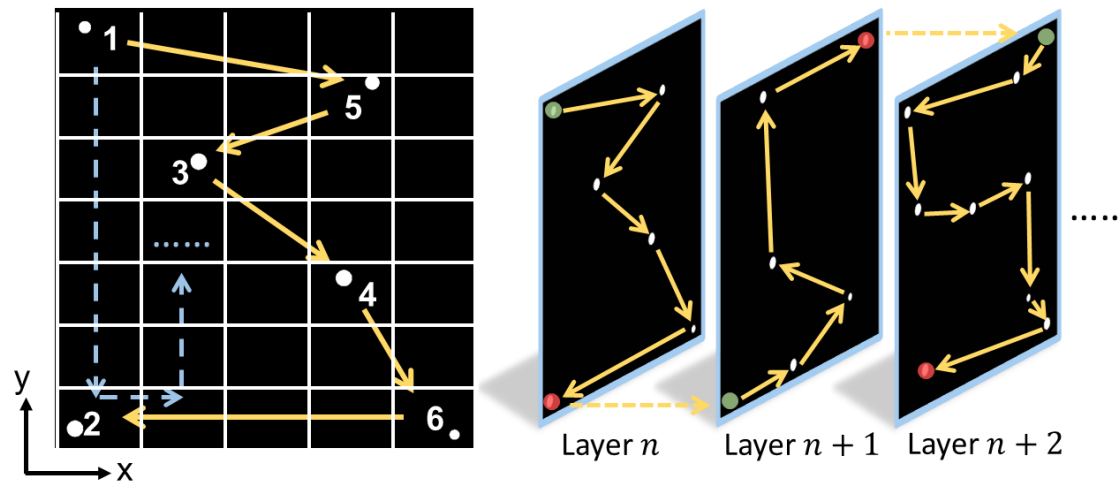
According to the simulated stress-strain curves, the absorbed energy was calculated, and the performance was compared with previously reported carbon-based energy absorption materials

Printing Process – Optimization of the Scanning Path

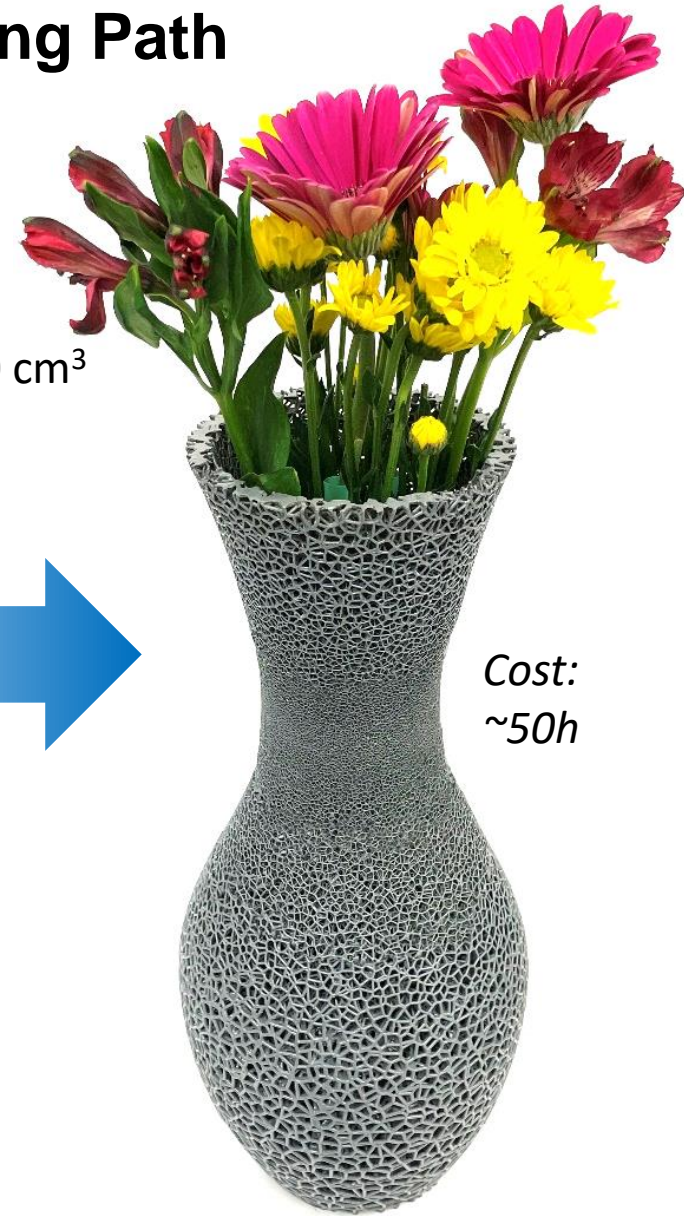
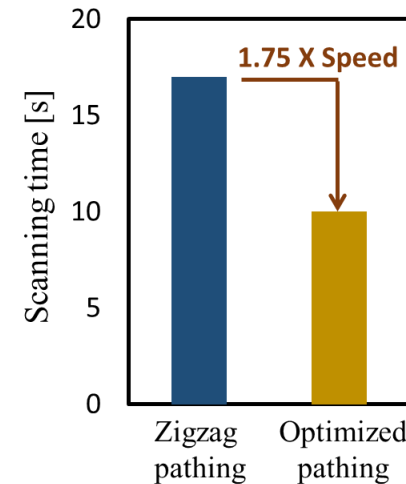
Image segmentation & scanning path optimization



Optimized Scanning Path (Traveling Salesman Algorithm)

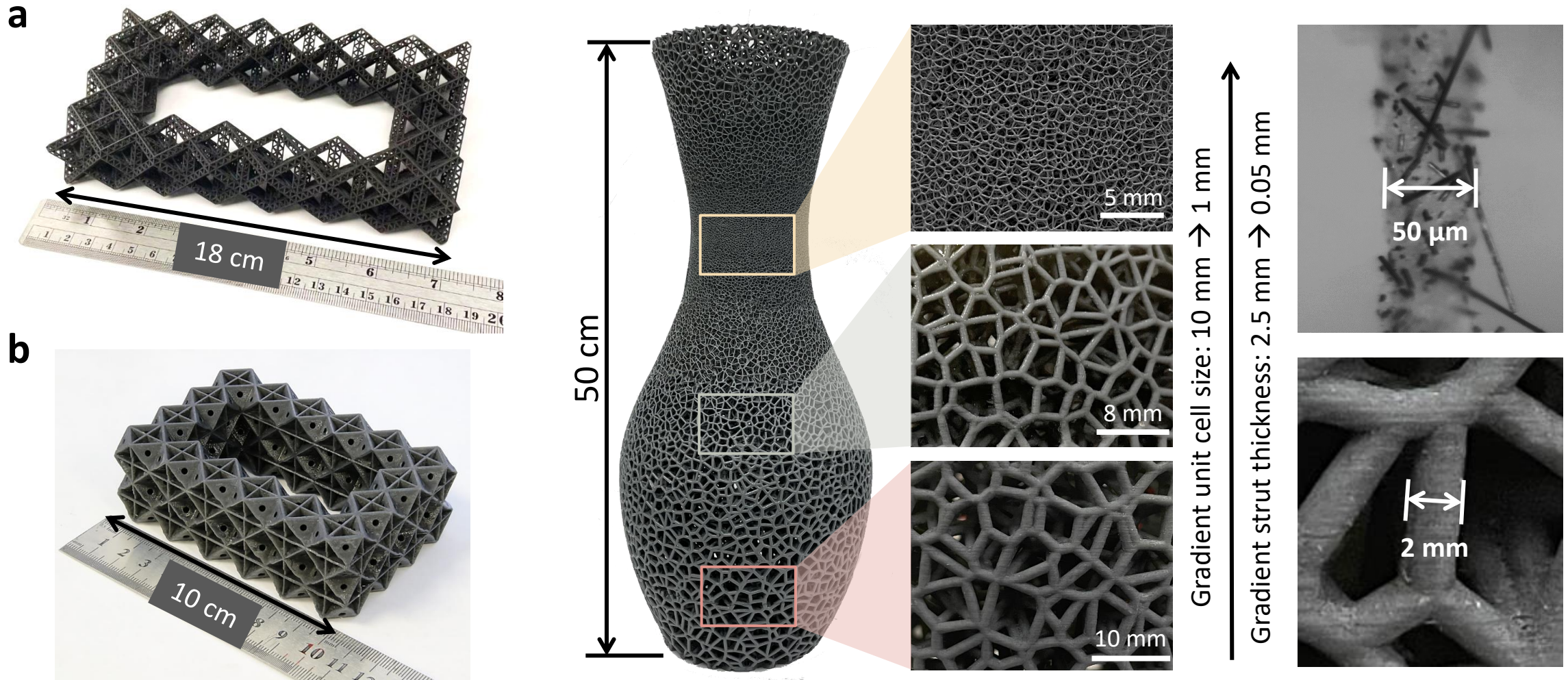


Overall size: $\sim 20 \times 20 \times 50 \text{ cm}^3$
Layer thickness: $50 \mu\text{m}$
Layers: $\sim 10,000$
Sub-images: $> 100,000$



We developed an optimization method to plan the scan path of each sub-section smartly, making the UV exposure process faster.

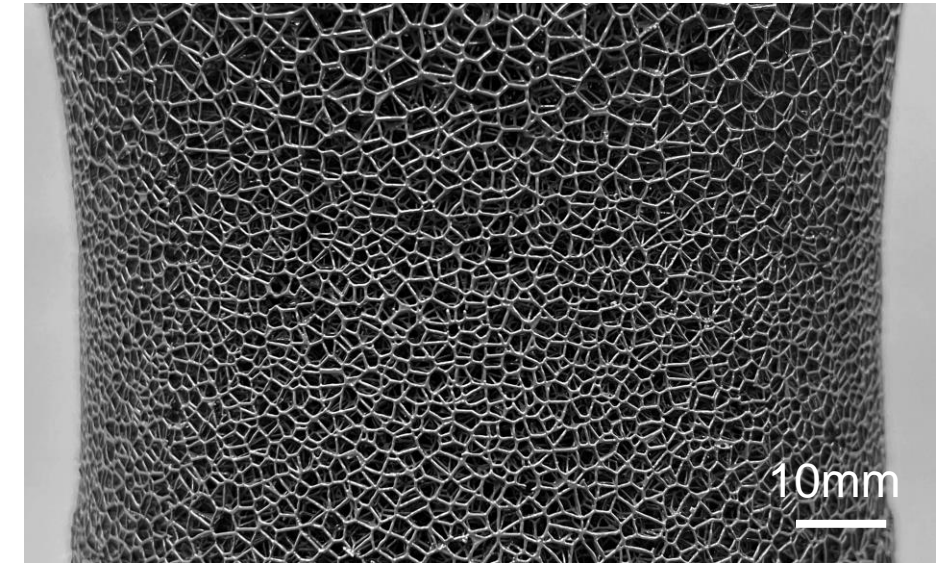
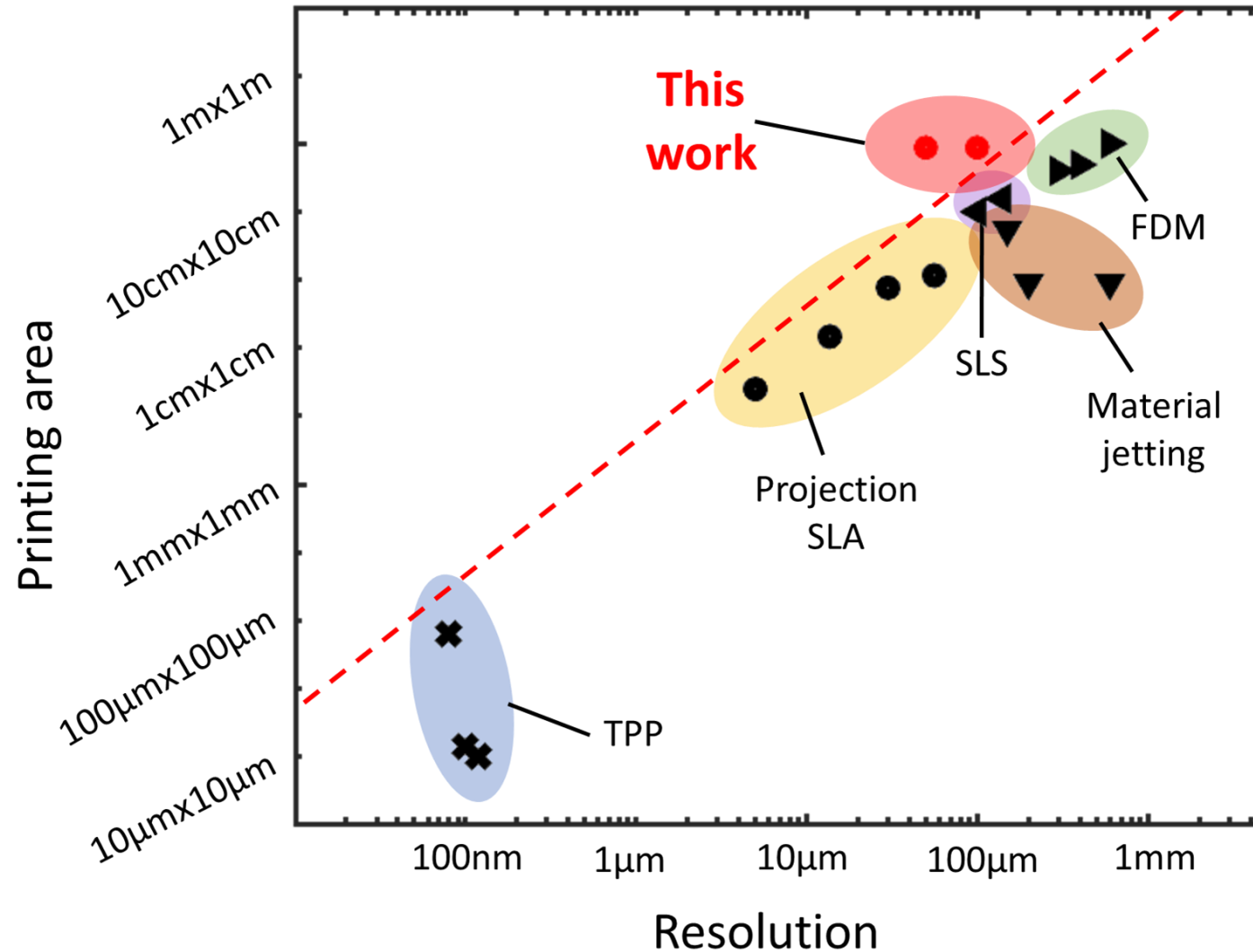
Large-scale CFRP Composites with Complex Micro-Architectures



CFRP lattice materials. (a) Large-scale hierarchical CFRP truss-lattice materials (strut radius = 150 μm). (b) Large-scale CFRP plate-lattice materials. (c) As-fabricated large-size high-resolution Voronoi vase made of CFRP.

Accomplishment: Achieved large-scale CFRP composites with complex 3D micro-architectures.

Benchmark with Other AM Techniques



Fabricated Voronoi lattice

- Minimal feature size: 50μm
- Printing volume: 30x22x50cm³
- Microscale features with a size span over 4 orders of magnitude can be fabricated

Ref: Ge et. al., International Journal of Extreme Manufacturing, 2020

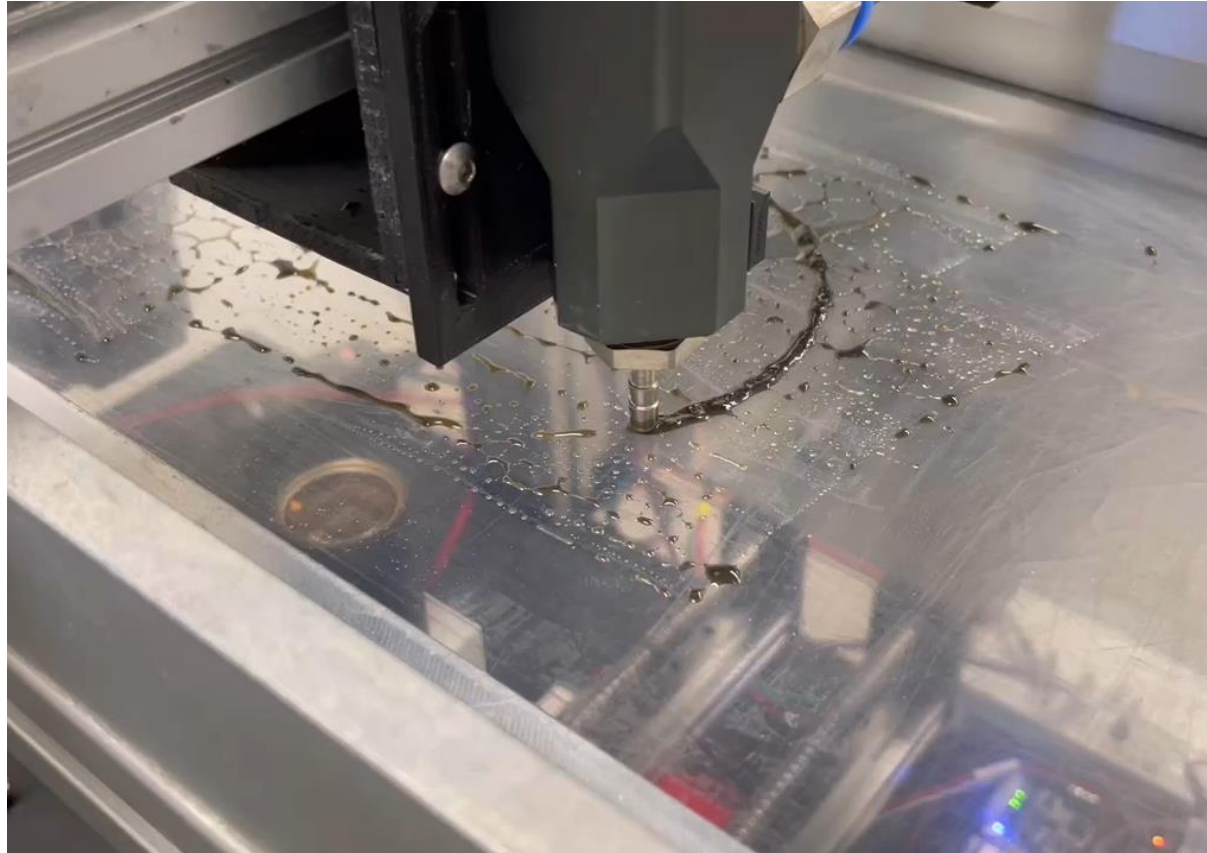
The developed system provides ability to scale up and scale down incoming image fields, thereby enabling the fabrication of architectures that have multi-scale features from tens of micrometers to hundreds of millimeters.

Technical Accomplishments

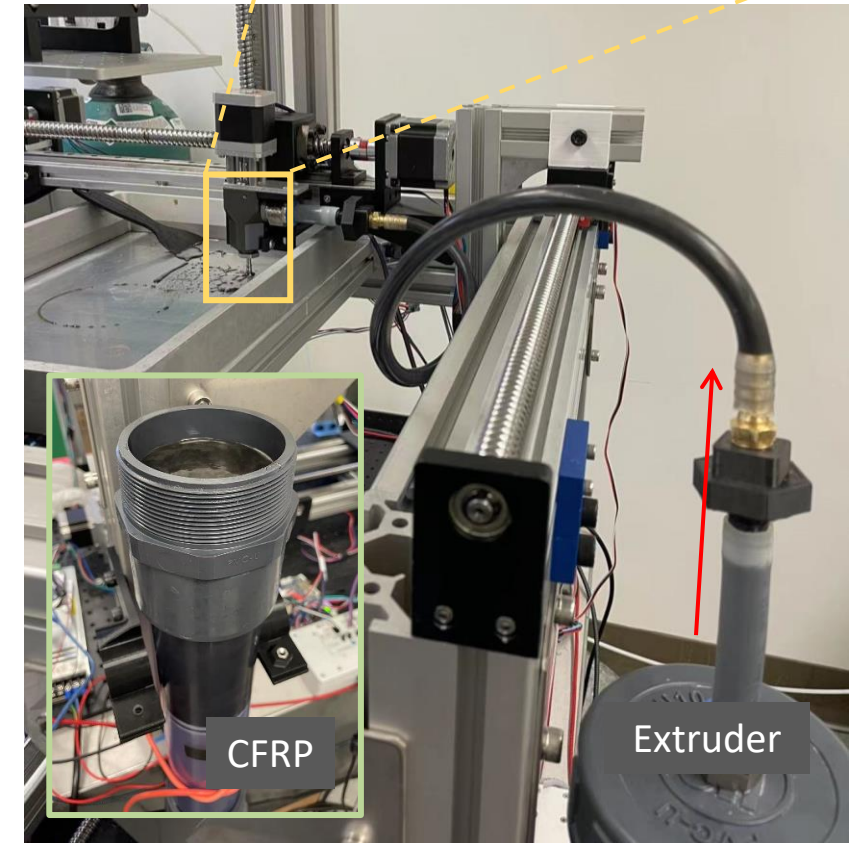
**Part 2 – Integration of moving optics system with
nozzle extrusion**

Extrusion System Setup

- To introduce fiber alignment, a custom extrusion system was developed and integrated to the printing system.
- With extrusion process, 2d alignment can be achieved.
- With scanning optical system, high-resolution 3d printing can be achieved.



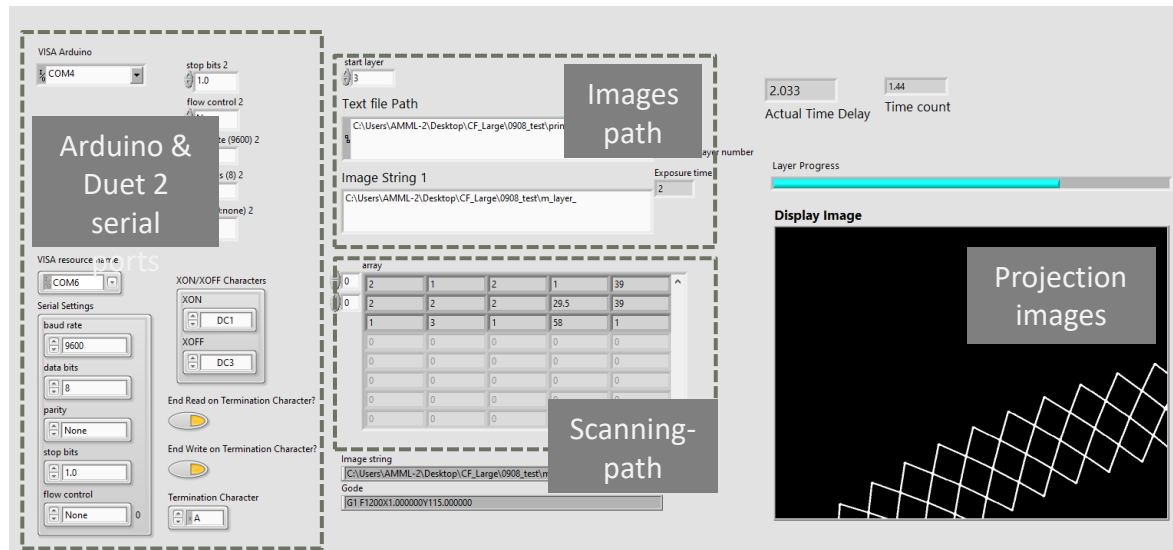
Motion setup for the 2d alignment



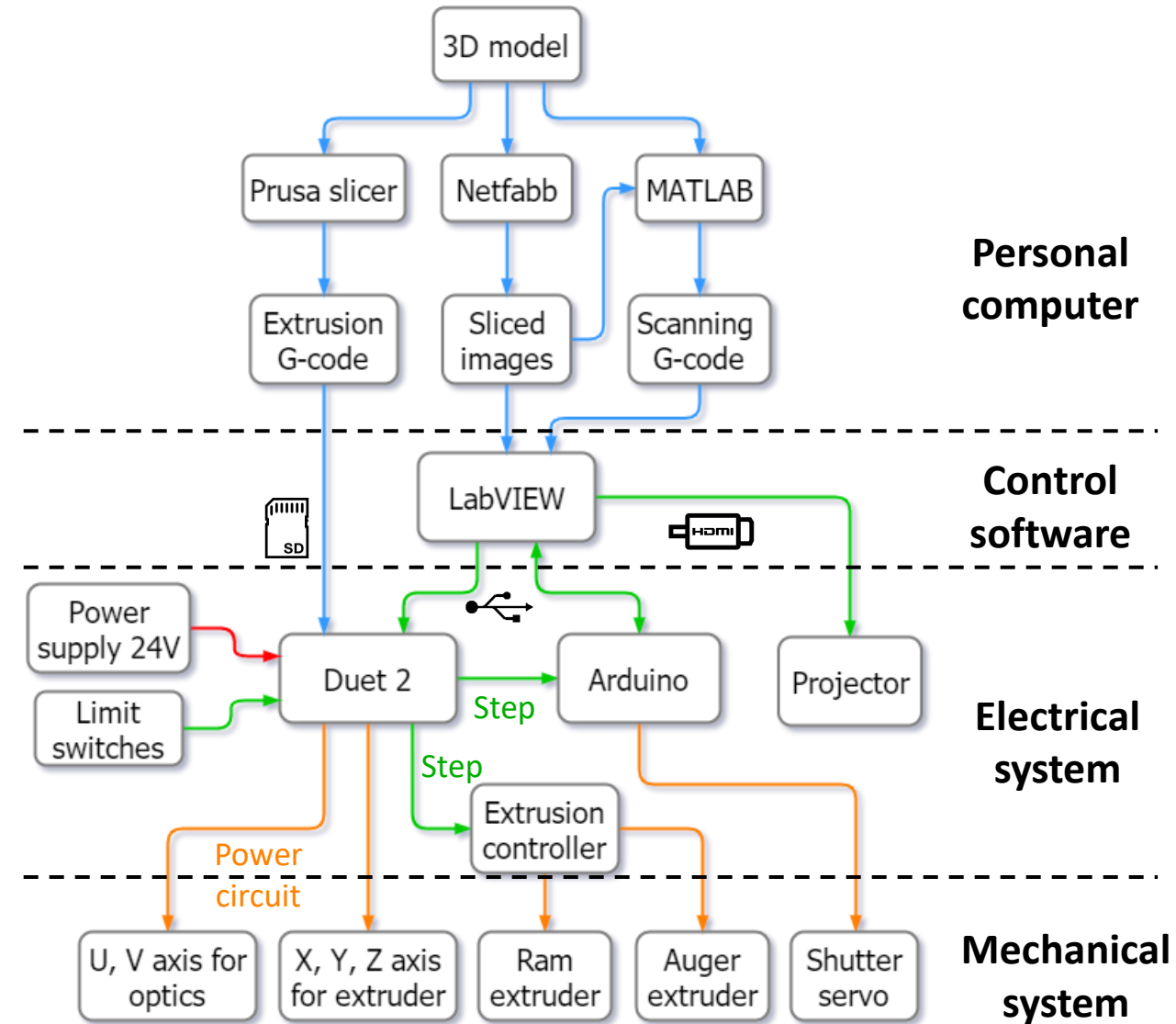
A hybrid printing process integrated with scanning optical and extrusion systems is developed. The system can achieve arbitrary 2d fiber alignment with high printing resolution.

Control System Development

- **Slicing software**
Prusa slicer, Netfabb, MATLAB
- **Programming language**
G-code, C++ & LabVIEW
- **Microcontroller**
Arduino, DUET2



LabVIEW programming interface

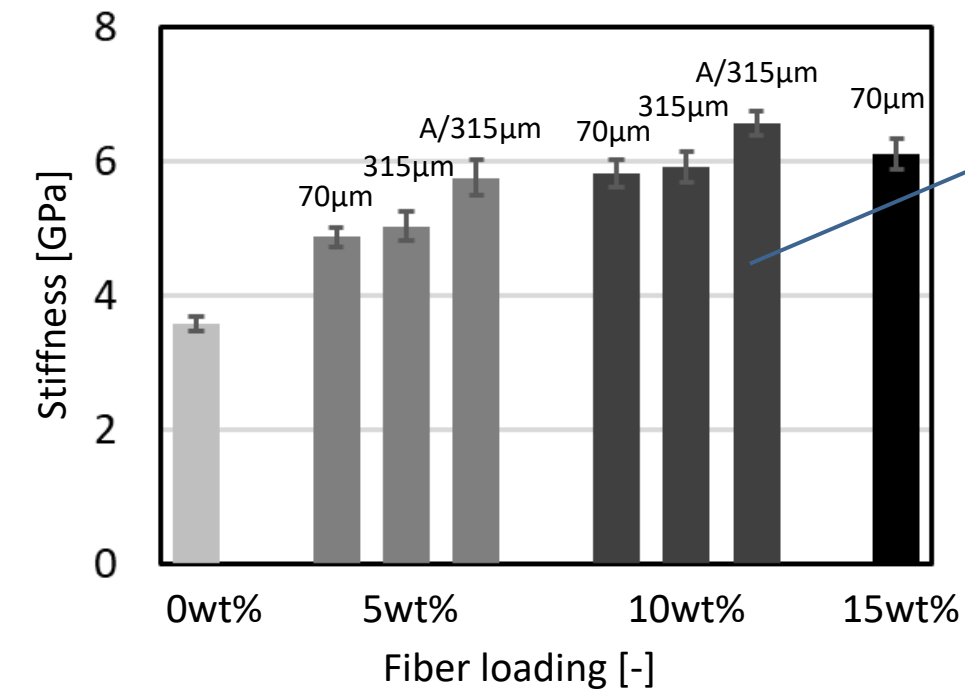


A custom control system was developed, including control software, electrical system, and mechanical system.

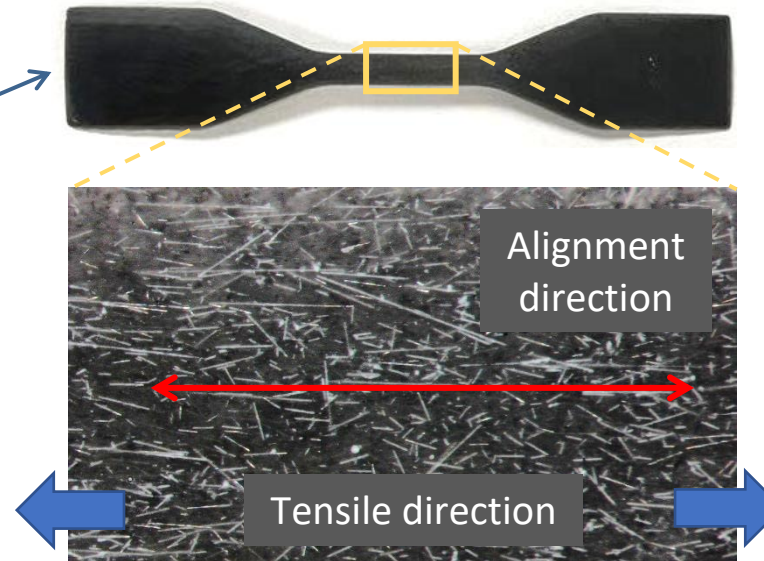
Base Material Property Measurement

- Monomer: Rigid resin; Average fiber length: 70 μ m/315 μ m.
- Fiber loading: 0-15wt%.
- Dog bones made of CFRP with different fiber loading were printed and tested.
- Conclusions:** 1. When fiber loading \uparrow , Young's Modulus \uparrow ; 2. With aligned fibers, the CFRP achieves a stiffness of 6.6GPa.

Fiber loadings (315 μ m)	Effective stiffness [MPa]	Ultimate strength [MPa]	Maximum strain [-]
0wt%	3575.5 \pm 105.8	40.5 \pm 4.45	3.85% \pm 0.32
5wt%	5031.5 \pm 219.3	35.17 \pm 3.08	1.1% \pm 0.1
5wt% (aligned)	5758.7 \pm 269.1	54.89 \pm 5.45	1.53% \pm 0.16
10wt%	5924.5 \pm 228.4	31.49 \pm 2.93	0.80% \pm 0.1
10wt% (aligned)	6576.5 \pm 180.3	32.74 \pm 4.88	1% \pm 0.15

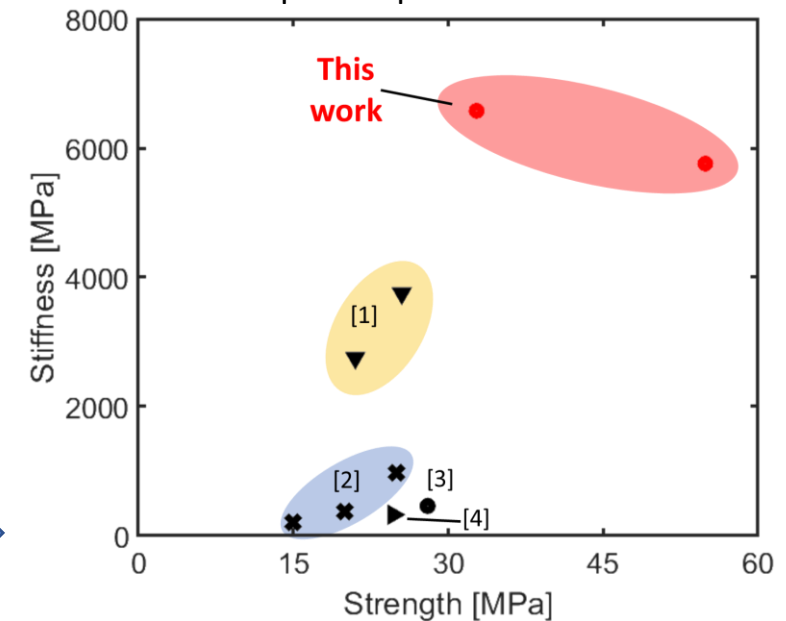


Stiffness of the CFRP bulk materials



CFRP sample with aligned fiber

Mechanical property map of fiber-reinforced composites printed via SLA



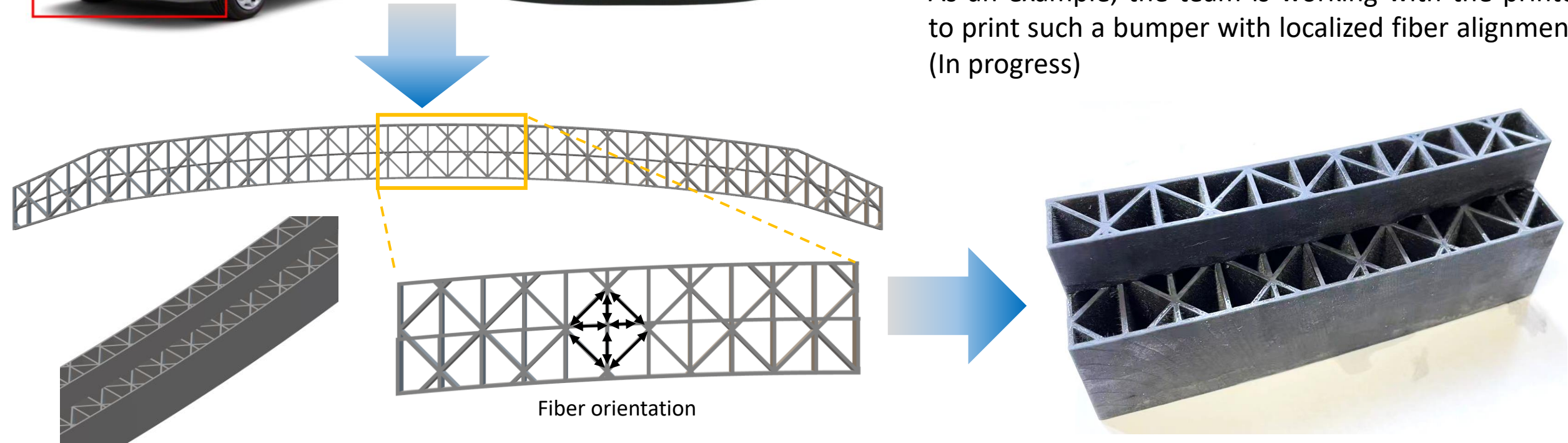
Ref: [1] Cheah et. al., *Rapid Prototyping Journal: Physical*, 1999; [2] Sano et. al., *Additive Manufacturing*, 2018; [3] Xiao et. al., *Nanotechnology*, 2021; [4] Zhang et. al., *Materials & Design*, 2021

CFRP composites with different fiber loading were printed and tested. By introducing fiber alignment, the CFRP achieves a Young's Modulus of 6.6GPa, far exceeding other works.

Application: 3d Printed Architected Lightweight Car Bumper



- A hollowed car bumper was designed with nTopology software by ORNL.
- Localized fiber alignment is desired to improve the strength of the part.
- As an example, the team is working with the printer to print such a bumper with localized fiber alignment. (In progress)



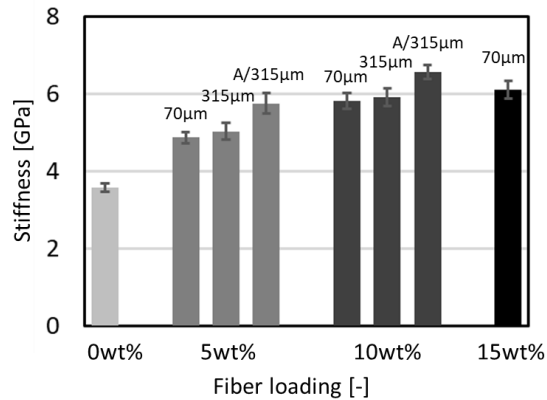
Hollowed car bumper design with localized fiber alignment directions

Part of 3d printed car bumper
(In progress)

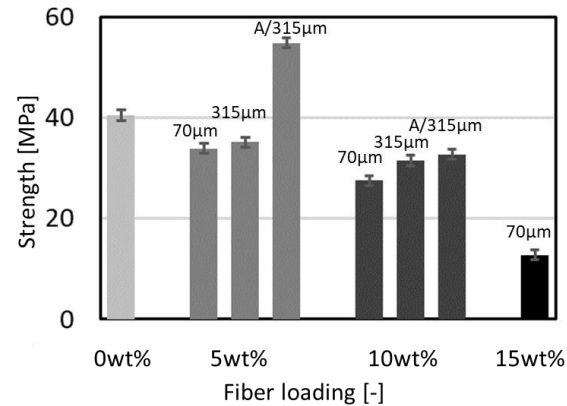
The team is working on demonstrating the application of such a printing system on 3d printed architected lightweight car bumper with localized fiber alignment.

Responses to Previous Year Reviewers' Comments -1

- **Limited data or information on strength, fiber length effects, fiber orientation, and fiber volume fraction effects on strength.**
 - Improved stiffness with carbon fibers—higher fiber volume fraction results in a higher stiffness but less strength.

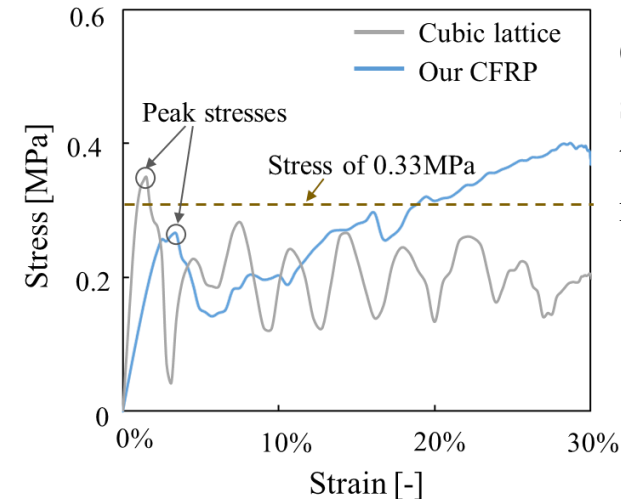


Stiffness of the CFRP bulk materials



Strength of the CFRP bulk materials

- **Strength and toughness relative to material performance requirements of components in commercial vehicles.**



Our CFRP lattice shows tunable stress-strain curves by reducing the impact stress while maximizing the energy absorption.

*The threshold of 0.33 MPa assumes the bone contact area of 0.012 m².

- **Improvement of speed.**
 - Compared with our previous year's work (~300 cm³/h), the new max throughput (900 cm³/h) increased by the factor of 3.
- **Anticipated performance increase by fiber alignment.**
 - With fiber alignment, the stiffness increased by 15 – 20% and the strength increased by 5 - 50%. (the first 2 figures)
- **The project approach addressed is not one of the prioritized barriers listed in U.S. DRIVE MTT Roadmap.**
 - “Under the U.S. DRIVE Partnership, the MTT adopted a 2025 partnership research target of a 25% glider mass reduction”
 - Our approach is to develop the optimal material/lattice/AM technology for lightweight, high stiffness, high damping structure.

Responses to Previous Year Reviewers' Comments -2

- **Milestones appear to have been modified from the 2020 AMR.**
 - Some of the milestones have been shifted to later dates. (Milestone 5 (due 12/31/2020) in AMR 2020 has simply been shifted to Milestone 4 (due 9/31/2021) in AMR 2021). Instead, we have developed plate-based multi-material lattice structures and improved strength-to-weight ratio significantly.
- **Target application**
 - Planning to fabricate a subcomponent of bumper next year. The technology can be applied to fabricating lightweight lattice structures in general.
- **Roles and responsibilities of the partners, and the typical interaction timing.**
 - Information added in this year's presentation.

Collaboration and Coordination with Other Institutions

- **Subcontractor:** University of California, Los Angeles
 - Point of Contact: Xiaoyu (Rayne) Zheng
 - Team members: Zhenpeng Xu, Chan Soo Ha, Hannelore Hemminger

System Development:

- Projection SLA 3D Printer Development
- Controlling Technology Development
- Manufacturing & Testing

- **Collaboration & Coordination:** Biweekly meetings and additional discussions on an ad hoc basis.

Technical Discussions:

- Inputs in developing scale-up systems
- Technical advices on material and structure research
- Applications and Design Criteria

Proposed Future Research

- Hybrid CFRP extrusion and alignment
 - Optimize shear rate and fiber orientations based on different aspect ratios
 - Achieve 3d printing of car bumper demo with localized fiber alignment
- Integrate multi-material exchange for soft inclusions within CFRP
 - Develop large-scale CFRP lattice material with high damping and stiffness
- Printing and testing of self-sensing structures
 - Rheology and UV curing study of matrix material and carbon fiber of various sizes
 - Demonstrate multi-functional self-sensing carbon fiber reinforced composites

“ Any proposed future work is subject to change based on funding levels”

Summary

- Target: Develop an AM technology for hybrid hierarchical carbon fiber-reinforced materials that are ultralight, strong and tough for 3D printing.
- Developed: Multi-material plate-based lattice structures with high stiffness and high energy absorption.
- Next phase: Demonstrate hierarchical CFRP lattice material with large scale (~50 cm), with tunable stiffness and energy-absorbing capabilities.

Publication

- [1] Xu, Z., Ha, C.S., Kadam, R., Lindahl, J., Kim, S., Wu, H.F., Kunc, V. and Zheng, X., 2020. Additive manufacturing of two-phase lightweight, stiff and high damping carbon fiber reinforced polymer microlattices. *Additive Manufacturing*, 32, p.101106.
- [2] Hsieh, M.T., Ha, C.S., Xu, Z., Kim, S., Wu, H.F., Kunc, V. and Zheng, X., 2021. Stiff and strong, lightweight bi-material sandwich plate-lattices with enhanced energy absorption. *Journal of Materials Research*, 36(18), pp.3628-3641.
- [3] Xu, Z., Hensleigh, R., Gerard, N.J., Cui, H., Oudich, M., Chen, W., Jing, Y. and Zheng, X.R., 2021. Vat photopolymerization of fly-like, complex micro-architectures with dissolvable supports. *Additive Manufacturing*, 47, p.102321.
- [4] Gerard, N.J., Oudich, M., Xu, Z., Yao, D., Cui, H., Naify, C.J., Ikei, A., Rohde, C.A., Zheng, X.R. and Jing, Y., 2021. Three-dimensional trampolinelike behavior in an ultralight elastic metamaterial. *Physical Review Applied*, 16(2), p.024015.
- [5] Wang, J., Papathanasopoulos, A., Rahmat-Samii, Y., Hensleigh, R., Xu, Z. and Zheng, X., 2021. Ultra-Lightweight Transmitarray Antenna Enabled by Charge-Programmed Three-Dimensional Multi-Material Printing.